

WR 7a: a V Sagittae or a qWR star?^{*}

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ABSTRACT

The star WR 7a, also known as SPH 2, has a spectrum that resembles that of V Sagittae stars although no O VI emission has been reported. The Temporal Variance Spectrum – TVS – analysis of our data shows weak but strongly variable emission of O VI lines which is below the noise level in the intensity spectrum.

Contrary to what is seen in V Sagittae stars, optical photometric monitoring shows very little, if any, flickering. We found evidence of periodic variability. The most likely photometric period is $P_{phot} = 0.227(\pm 14)$ d, while radial velocities suggest a period of $P_{spec} = 0.204(\pm 13)$ d. One-day aliases of these periods can not be ruled out. We call attention to similarities with HD 45166 and DI Cru (= WR 46), where multiple periods are present. They may be associated to the binary motion or to non-radial oscillations.

In contrast to a previous conclusion by Pereira et al. (1998), we show that WR 7a contains hydrogen. The spectrum of the primary star seems to be detectable as the N V 4604 Å absorption line is visible. If so, it means that the wind is optically thin in the continuum and that it is likely to be a helium main sequence star.

Given the similarity to HD 45166, we suggests that WR 7a may be a qWR – quasi Wolf-Rayet – star. Its classification is WN4h/CE in the Smith, Shara & Moffat (1996) three dimensional classification system.

Key words: stars: individual: WR 7a – stars: Wolf-Rayet – stars: fundamental parameters – stars: emission-line.

1 INTRODUCTION

The star WR 7a was observed by Schwartz, Persson & Hamann (1990) - SPH - as part of a survey to characterize stars previously identified as H α emission sources. Pereira et al. (1998) classified it is a WR star of type WN4, with a strong emission of C IV 5801 Å. This line, however, is characteristic of the WC class. WR 7a is situated in an intermediate stage between the WN and the WN/WC stars, a category of WR stars discussed by Conti & Massey (1989). On the basis of the He II Pickering decrement Pereira et al. (1998) suggested that the star has no hydrogen. Those authors determined a colour excess of $E(B - V)$ between 1.2 and 2.1, derived from diffuse interstellar bands, and used the convolution of the spectrum with a V filter profile to measures a V magnitude of 15.0. The star was included in the VIIth Catalogue of

Galactic Wolf-Rayet stars (van der Hucht 2001) under the designation WR 7a and we will here adopt this designation instead of the name SPH 2 under which it was previously known.

In a search for new stars of the V Sagittae class (Steiner & Diaz 1998), we selected WR 7a as a candidate because of the similarity of its spectrum to that of V617 Sgr, in spite of the absence of the O VI lines.

The V Sagittae stars form a group of 4 galactic binaries: V Sge (Herbig et al. 1965; Diaz 1999), WX Cen (Diaz & Steiner 1995), V617 Sgr (Steiner et al. 1999; Cieslinski, Dias & Steiner 1999) and DI Cru (= WR 46) (Marchenko et al. 2000). They are characterized by the presence of strong emission lines of O VI and N V. Moreover, He II 4686 Å is at least two times more intense than H β + He II 4859 Å. The spectra of the V Sagittae stars do not show any indication of the secondary component. The orbital light curves of the members of this class are either low-amplitude sine waves or are asymmetric with higher amplitude, the latter characterized by primary and secondary eclipses with different depths. The orbital periods range from 5 to 12 h. The V Sagittae stars are observationally very similar to the

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Compact Binary Supersoft Sources (CBSS), which are more abundant in the Magellanic Clouds than in the Galaxy.

The CBSS exhibit very soft X-Ray spectra and high luminosities, and are interpreted as suffering hydrostatic hydrogen nuclear burning on the surface of a white dwarf (van den Heuvel et al. 1992). This burning is due to high mass transfer rates from the secondary stars in consequence of the fact that these systems have secondaries more massive than the primaries (see Kahabka & van den Heuvel (1997), for a review and references therein).

In the following section we describe our photometric and spectroscopic observations of WR 7a and the reductions of the data, while in section 3 we present the results of the analysis. The conclusions of this work are presented in section 4.

2 OBSERVATIONS

We made photometric measurements of the star WR 7a with the Boller & Chivens 60-cm telescope of the University of São Paulo and the Zeiss 60-cm telescope, both located at the Laboratório Nacional de Astrofísica (LNA), in Itajubá, southeast Brazil. We used the thin, back-illuminated EEV CCD 002-06 chip and a Wright Instruments thermoelectrically cooled camera. The timing was provided by a Global Positioning System (GPS) receiver. Table 1 contains a journal of the CCD observations. The images were obtained through the Johnson *V* band and were corrected for bias and flatfield, using the standard IRAF¹ routines. The star is located in a quite rich field; therefore, we carried out differential PSF (Point Spread Function) photometry of WR 7a and four comparison stars using the LCURVE package, written and kindly provided by M.P. Diaz. It makes use of DAOPHOT routines to treat automatically long time series data.

Spectroscopic measurements of WR 7a were carried out with the Cassegrain spectrograph coupled to the 1.6-m telescope at the LNA. We used a 900 lines per mm dispersion grating, covering the spectrum from 3650 Å to 4950 Å – see Table 1. We used a thin, back-illuminated SITe SI003AB 1024x1024 CCD. Bias and dome flatfield exposures were obtained to correct for the read-out pattern and sensitivity of the CCD. The width of the slit was adjusted to the seeing conditions at the time of observations. We took exposures of calibration lamps after every third exposure of the star, in order to determine the wavelength calibration solution. The image reductions, spectra extractions and wavelength calibrations were executed with IRAF standard routines, and the measurements of the He II 4686 Å radial velocities were done by fitting gaussian functions to the peaks of these emission lines.

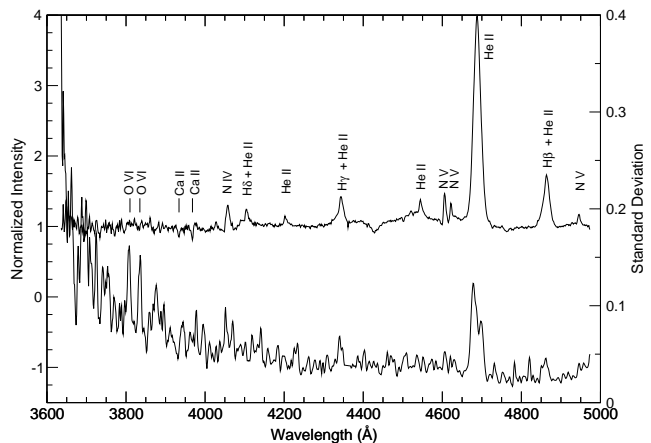


Figure 1. Intensity spectrum (above) and Time Variance Spectrum (below) of WR 7a.

3 DATA ANALYSIS AND DISCUSSION

3.1 Analysis of the optical spectrum: the variable O VI lines

The spectrum of WR 7a is very similar to those of V Sagittae stars, except for the absence of O VI emission lines. In particular, the similarity between its spectrum and that of V617 Sgr (Steiner et al. 1999) is remarkable. The properties of the most prominent lines of WR 7a are presented in Table 2. In order to examine in more detail the characteristics of the spectrum we performed a Temporal Variance Spectrum (TVS) analysis. In this analysis we normalize all spectra in such a way that the continuum is equal to 1. The temporal variance is calculated for each wavelength pixel. In our TVS spectra we calculated the square root of the variance as a function of wavelength. For a more detailed discussion of this method see Fullerton, Gies & Bolton (1996). Figure 1 shows the the intensity spectrum and the TVS for WR 7a. Although below the noise level in the intensity spectrum, the O VI 3811/34 Å emission lines are easily visible in the TVS, indicating their high variability. WR 7a displays, therefore, all the spectroscopic features that characterize the V Sagittae stars such as the high He II/H β ratio and the simultaneous presence of O VI and N V lines.

3.2 Searching for periodicities

The light curves of the four observed nights are quite flat, with very little, if any, flickering. V Sagittae stars have, as a rule, significant variability on time-scales of tens of minutes. In addition, the orbital variations are easily recognizable in light curves of V Sagittae stars but not in WR 7a. Thus, from the photometric point of view, WR 7a does not behave like the V Sagittae stars.

We used our radial velocity and photometric data to search for possible periodicities. The Lomb-Scargle periodogram (Scargle 1982) of the He II 4686 Å radial velocity measurements from our spectra is presented in Figure 2. We also show, in Figure 3, the periodogram of the photometric measurements. The latter was constructed on the basis of data from the two consecutive nights of 2000 May

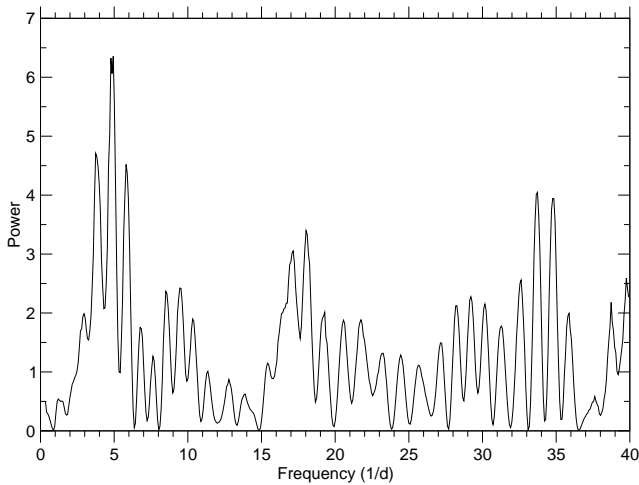
¹ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Journal of photometric and spectroscopic observations of WR 7a.

Date	Telescope	Instrument	CCD	Number of exps.	Exp. time (s)	Filter	grating (1/mm)	Resol. (Å)
23/01/2000	B&C 60 cm	Imaging Camera	301	165	150	V
02/02/2000	Zeiss 60 cm	Imaging Camera	301	1180	15	V
02/05/2001	Zeiss 60 cm	Imaging Camera	301	363	20	V
03/05/2001	Zeiss 60 cm	Imaging Camera	301	360	30	V
02/02/2000	B&C 1,6 m	Cassegrain Spectr.	106	32	600	...	900	2.8
03/02/2000	B&C 1,6 m	Cassegrain Spectr.	106	11	900	...	900	2.8

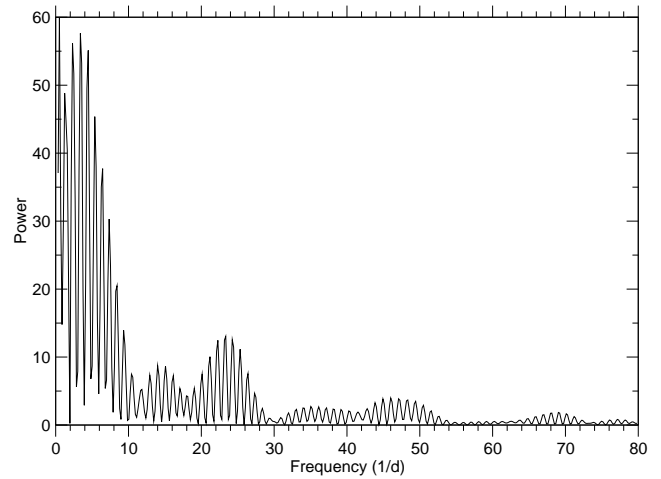
Table 2. Spectral line properties of WR 7a.

Species	Observed wavelength (Å)	W_λ (Å)	FWHM (km s ⁻¹)
Ca II	3933.73	0.54	249:
Ca II	3967.77	0.57	147:
He II	4028.00	-0.75	420
N IV	4057.70	-4.2	763
H δ	4104.93	-1.0	436
He II	4203.5:	-1.5:	884:
H γ	4343.7:	-5.6:	1109:
He II	4544.60	-0.45	206
N V	4604.24	-2.9	383
N V	4621.82	-1.2	276
He II	4688.10	-63	1389
H β	4863.93	-15.3	1209
N V	4945.51	-0.90	349

**Figure 2.** Lomb-Scargle periodogram of the He II 4686 Å radial velocities data.

2 and 3. The data from the other observing nights were non-consecutive and too far apart to be included in the periodogram analysis.

The highest peak seen in the Lomb-Scargle periodogram (Figure 2) of the radial velocity data corresponds to a period of 0.204 d ($f = 4.9 \text{ d}^{-1}$). The photometric data (Figure 3) yield a slightly different value, 0.227 d ($f = 4.4 \text{ d}^{-1}$). Given the limited time coverage of our data, the errors involved are quite large. The two periods differ by 1.7σ . This

**Figure 3.** Lomb-Scargle periodogram of the photometry data.

means that there is a non-negligible chance that they are actually identical. One-day aliases of these periods can not be ruled out. Period values such as these, or multiple periodicities, are not unusual in systems like WR 7a. The orbital period of the V Sagittae star V617 Sgr, for instance, is 0.208 d (Steiner et al. 1999), while the qWR star HD 45166 (Steiner & Oliveira, in preparation) and the WR star DI Cru (Marchenko et al. 2000; Veen et al. 2002) are systems with multiple periods that probably include the orbital period plus a number of possible periods due to non-radial pul-

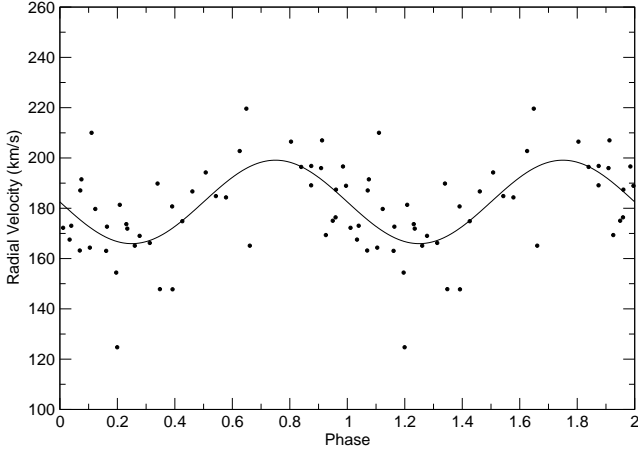


Figure 4. Radial velocity curve of the He II 4686 Å emission line, folded to the 0.204 d period. The continuous line is the best-fitting sine curve.

sations. We do not claim that WR 7a is necessarily a binary system. Candidates to non-radial pulsations in the stars HD 45166 and DI Cru are in the range from 0.2 to 0.4 d. Given the experience with these systems, a lot more spectra with higher spectral resolution and higher signal-to-noise ratio are required to clarify the nature of these periods – or, eventually, of this single period – in WR 7a.

The radial velocity and photometric ephemerides are

$$T_{\text{spec}}(HJD) = 2\,451\,577.692(\pm 20) + 0.204(\pm 13) \times E \quad (1)$$

and

$$T_{\text{phot}}(HJD) = 2\,452\,032.600(\pm 23) + 0.227(\pm 14) \times E \quad (2)$$

where zero phase of the radial velocity ephemeris is defined as the crossing from positive to negative values, and T_{phot} are timings of minimum brightness. The radial velocity curve of the He II 4686 Å line, folded to the 0.204 d period is shown in Figure 4. It presents sinusoidal variations with an amplitude of about $K \sim 17 \text{ km s}^{-1}$. The average light curve folded to the 0.227 d period is shown in Figure 5, and presents a peak-to-peak amplitude of 0.02 mag.

An additional (weak) signal is seen in the photometric periodogram (Figure 3), where one can see power excess at about 60 min ($f = 24 \text{ d}^{-1}$). Theoretical studies on radial pulsations of Wolf-Rayet stars (Maeder 1985) indicate oscillation periods in the range of 15 to 60 min. Blecha, Schaller & Maeder (1992) claim to have seen similar oscillations with period of 10 min in WR 40, but their reality has been questioned (Marchenko et al. 1994). Further investigation of this particular issue is certainly desirable.

3.3 The Hydrogen content

Pereira et al. (1998) claimed that WR 7a does not present hydrogen emission. They concluded this on the basis of their He II Pickering decrement analysis. A re-analysis of the equivalent widths presented by these authors, however, shows that this conclusion is not correct. We applied a procedure in which we compared theoretical (Osterbrock 1989) and observed equivalent widths of the He II lines of

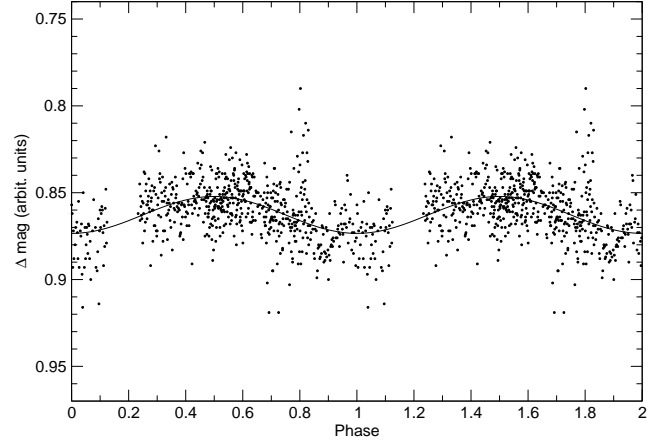


Figure 5. Average light curve folded to the 0.227 d period. The continuous line is the best-fitting sine curve.

the Pickering series, normalized to the equivalent width of He II 5411 Å. The result is shown in Figure 6. The oscillatory behavior associated to the presence of hydrogen is clearly noticed.

Another way to investigate the presence/absence of hydrogen in a spectrum with strong helium emission consists in comparing the He II 4859 Å+H β strength with the geometric mean of the strength of the two adjacent transitions from the Pickering series. This criterion has been widely used, for instance, by Smith, Shara & Moffat (1996) in defining their three-dimensional classification of WN stars. We define the Pickering parameter, p , such that

$$p = \frac{I(4859\text{Å} + 4861\text{Å})}{(I(4541\text{Å}) \times I(5411\text{Å}))^{1/2}} \quad (3)$$

For a pure He II spectrum one expects $p = 1$ (Smith, Shara & Moffat 1996). Any value of p larger than 1 would mean that hydrogen is present in the spectrum. In the case of WR 7a, the measured value is about $p = 1.88$.

If both hydrogen and helium lines were optically thin, it would be easy to determine the relative abundance between the two species. In this case (Conti, Leap & Perry 1983),

$$\frac{N(H^+)}{N(He^{++})} = p - 1 \quad (4)$$

and $H/He \sim 0.88$. The largest uncertainty in this determination comes from the hypothesis that all of the involved lines are optically thin.

For the optically thick case, one gets (see Conti, Leap & Perry (1983))

$$\frac{N(H^+)}{N(He^{++})} = p^{3/2} - 1 \quad (5)$$

and the abundance is $H/He \sim 1.6$. As the TVS analysis shows some absorption in the He II line, it is probably optically thick at low velocities. At high velocities the wind is usually optically thin. In the present case we have, therefore, a situation that is likely to be intermediate between optically thick (line core) and optically thin (line wings) and the actual abundance is likely to be intermediate between the two values mentioned above.

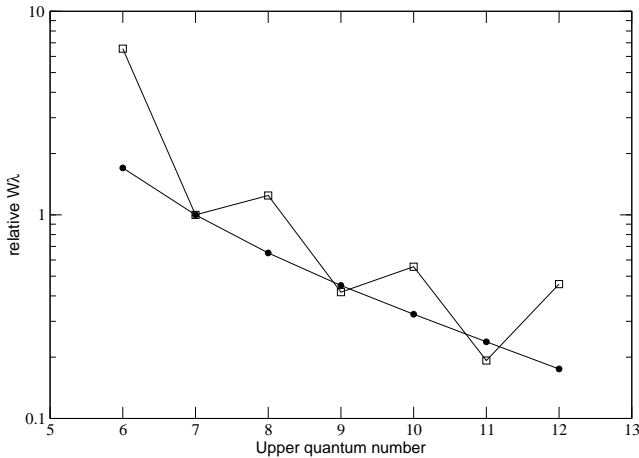


Figure 6. The He II Pickering series for WR 7a. Theoretical intensities for a pure He II spectrum are represented by filled circles and observed data are represented by empty squares.

3.4 Do we see a photospheric absorption line? – Comparison with HD 45166

In the spectrum of WR 7a published by Pereira et al. (1998) one can see a weak, but clearly present, absorption line at 4604Å. It is also (albeit barely) visible in our spectrum of poorer signal-to-noise ratio. This is not likely to be a P Cyg absorption because such features are not seen in the Balmer or He II lines.

We have seen a similar feature in the high resolution and high signal-to-noise spectrum of the qWR star HD 45166 (Steiner & Oliveira, in preparation). In that case, we identified this feature as a N V photospheric line of the hot primary, which is a helium main sequence star of about $3.5 M_\odot$. The IUE spectrum of HD 45166 (Willis & Stickland 1983) also shows photospheric lines of N V, Fe V, O V among others. This is a clear evidence that, in that star, the wind is optically thin at the continuum, contrary to what is usually the case in WR stars. This is not surprising, given that the mass-loss rate is about 1000 times smaller in HD 45166 than in WR stars. As the mass-loss rate is related to the stellar luminosity, and the latter to its mass (see Lamers & Cassinelli (1999)), and since we identify the N V absorption line of WR 7a as a photospheric feature, we conclude that WR 7a has a mass which is smaller than the mass of a typical WR star. On the other hand, the mass cannot be too small, otherwise its temperature would not be high enough to produce the N V lines or the O VI lines. The emission lines in WR 7a have equivalent widths that are about a factor of two stronger than in HD 45166, after correcting, in the latter case, for the strong contribution of the secondary. This also suggests that the mass-loss rate and the luminosity – and consequently, the mass – is higher than in HD 45166. In conclusion, WR 7a could be interpreted as a helium main sequence object with a mass that is intermediate between HD 45166 ($3.5 M_\odot$) and typical WR stars ($\sim 10 M_\odot$).

3.5 How to classify WR 7a?

The spectral characteristics of WR 7a indicate that it could be classified as a star of the V Sagittae type. It presents all the characteristics that define this class, such as the intensity ratio of He II 4686 Å and H β as well as the simultaneous presence of N V 4945 Å and O VI 3811/34 Å emission lines. However, the presence of the N V 4604 Å photospheric absorption line and the absence of flickering argue against this classification and point towards the similarities to HD 45166 (Steiner & Oliveira, in preparation), which has been classified as a qWR star (see Willis et al. (1989) and references therein). Although the observational differences between these two groups of stars are quite subtle, they follow very distinct paradigms in terms of their ultimate nature. While V Sagittae stars are interpreted as the galactic counterpart of CBSS and, therefore, accreting white dwarfs with hydrogen burning on their surface (Steiner & Diaz 1998; van den Heuvel et al. 1992), the qWR paradigm assumes a helium main sequence star (Steiner & Oliveira, in preparation).

In the three-dimensional classification system proposed by Smith, Shara & Moffat (1996) for WN stars, we classify WR 7a as WN4h/CE. This takes into account the degree of ionization (He II to He I line ratio), the presence and abundance of hydrogen, the He II 4686 Å line width and the strength of the C IV 5801/11 Å emission lines.

4 CONCLUSIONS

The main conclusions of this paper are:

- (1) The star WR 7a = SPH 2 has a spectrum that resembles that of V Sagittae stars.
- (2) TVS analysis shows strong variability in the O VI lines. They are below the noise level in the intensity spectrum.
- (3) Contrary to what is seen in V Sagittae stars, optical photometric monitoring shows very little, if any, flickering.
- (4) We found evidence of periodic variability. The most likely spectroscopic period is $P_{spec} = 0.204$ d, with $K \sim 17$ km s $^{-1}$. Photometry suggests a period of $P_{phot} = 0.227$ d, and a peak-to-peak amplitude of 0.02 mag. One-day aliases of these periods can not be ruled out. We do not claim that these periods are distinct, nor that WR 7a is necessarily a binary system.
- (5) We call attention to similarities with HD 45166 and DI Cru, where multiple periods are present, which may be associated to the binary motion and/or non-radial oscillations.
- (6) Contrary to what was claimed by Pereira et al. (1998), we show that WR 7a contains hydrogen. We determine the H/He abundance, by number, to be between 0.88 (optically thin approximation) and 1.6 (optically thick approximation).
- (7) The spectrum of the primary star seems to be detectable as the N V 4604 Å absorption line is visible. If so, it means that the wind is optically thin in the continuum and that WR 7a is likely to be a helium main sequence star.
- (8) Given the similarity to HD 45166, we suggest that WR 7a may be a qWR (quasi Wolf-Rayet) star. Its WR classification is WN4h/CE.

5 ACKNOWLEDGMENTS

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